



# Environmental Dependence of Nonlinear Relationships between Fractional Vegetation Cover and Ecosystem Services Based on the Constraint Line Approach

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## Abstract

Afforestation is often portrayed as a panacea for ecosystem service (ES) degradation and climate change, yet it is criticized for overlooking potential risks, highlighting the limited understanding of its effects across contexts. This study aimed to reveal the environmental dependence of nonlinear ES responses to fractional vegetation cover, in order to provide guidance for landscape management and decision-making. We quantified the spatiotemporal changes in FVC and three ESs, as well as the correlations between them, on the Loess Plateau from 2000 to 2022, using various quantitative assessment models, the Mann–Kendall test, and Pearson correlation analysis. We further used constraint-line methods to identify nonlinear FVC–ES relationships and threshold effects across precipitation gradients and geomorphological types. FVC is strongly positively associated with carbon sequestration and soil retention (in >80% of the region), but shows a positive association with water yield in only 36.5% of the region. Plateau-wide FVC thresholds are substantially higher than those in arid and semi-arid zones and in plains. Ignoring this discrepancy risks setting unrealistically high restoration targets in drylands. Precipitation exerts a much stronger control on FVC thresholds than geomorphology, and its marginal effect declines with increasing precipitation. These findings clarify how vegetation restoration affects ecosystem services and provide a basis for ecological restoration strategies on the Loess Plateau and in arid and semi-arid regions worldwide.

Xiaoman Liu and Bingbing Gao contributed equally to this work.

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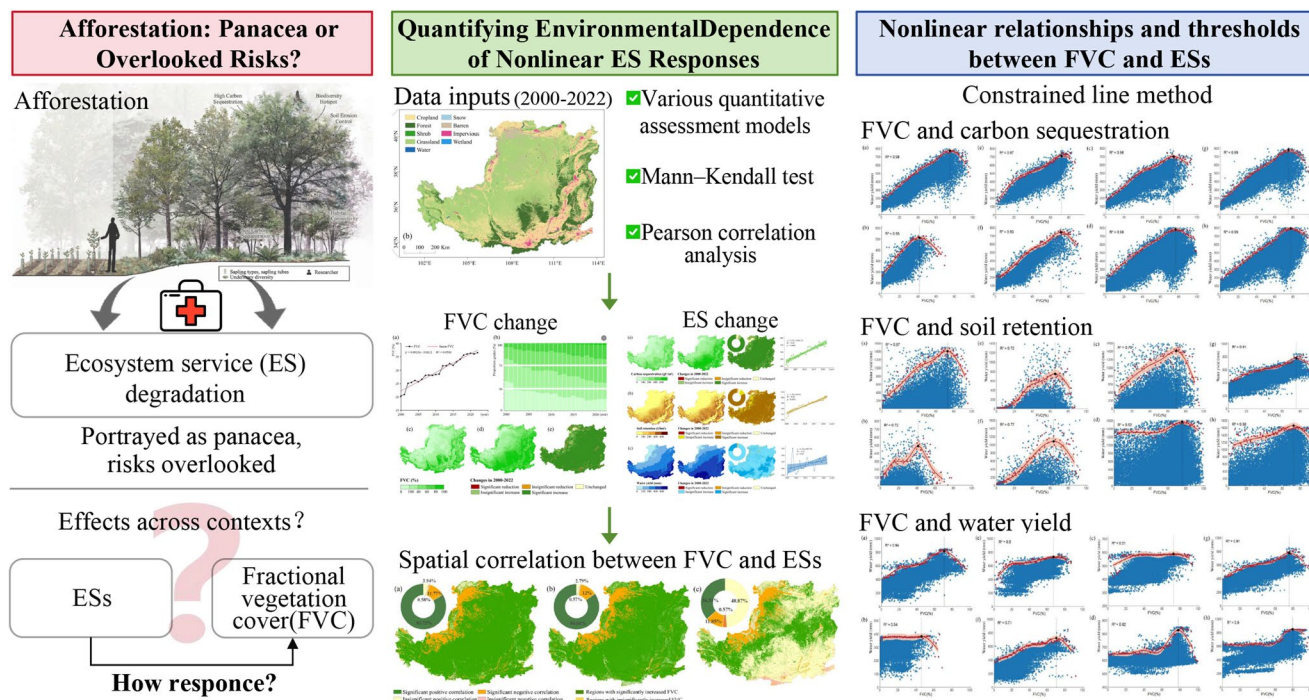
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## Graphical abstract



Under the backdrop of global greening, how differing climatic and geographic conditions modulate the nonlinear responses between afforestation and ecosystem services (ESs) remains poorly understood. Using the Loess Plateau—an emblematic region for global afforestation—as the study area, this study employed various quantitative assessment models, the Mann–Kendall test, and Pearson correlation analyses to characterize the spatiotemporal dynamics and spatial correlations between fractional vegetation cover (FVC) and ESs over 2000–2022. We further applied constraint-line methods to identify nonlinear FVC–ES relationships and threshold effects along precipitation gradients and across geomorphological types. The results demonstrate that the nonlinear ES responses to FVC are strongly environment-dependent, and that precipitation exerts a substantially greater control over FVC threshold behavior than geomorphology. Moreover, we elucidate the potential risks associated with neglecting natural environmental conditions. Collectively, these findings provide critical scientific evidence for ecosystem management and ecological restoration policies on the Loess Plateau and in arid and semi-arid regions worldwide.

## Highlights

- Quantified nonlinear response of ESs to FVC using the constraint-line method;
- Identified potential risks of identifying FVC thresholds at a single scale;
- Analyzed FVC threshold effects on ESs from multidimensional perspectives.

**Keywords** Ecosystem Services · Fractional Vegetation Cover · Threshold · Multi-Scale · Loess Plateau

## 1 Introduction

Tree planting is often promoted as a “panacea” because of its multiple benefits, including improved water quality, reduced soil erosion, and climate change mitigation (Erbaugh and Oldekop 2018; Alba-Patino et al. 2021; Yue et al. 2024). Over the past two decades, global vegetation cover has increased by 550 million hectares, nearly equivalent to the size of the Amazon rainforest (Li et al. 2024).

However, the potential risks associated with tree planting are often overlooked (Bustamante et al. 2019; Holl and Brancalion 2020; Li et al. 2021). For example, large-scale afforestation in China has altered the water cycle, resulting in a reduction of wetland areas by 1,300–1,500 square kilometers (Xi et al. 2022). Existing studies lack a comprehensive understanding of how afforestation affects ecosystem services (ESs) (Laudari et al. 2022; Li et al. 2022; Sarira et al. 2022). Therefore, understanding the complex relationships between afforestation and ESs is essential for

formulating ecological restoration targets and optimizing restoration practices.

The increase in vegetation affects ESs through complex nonlinear relationships (Zhang et al. 2022; Liu et al. 2025). Traditional analytical methods, such as correlation analysis, regression analysis, and elasticity coefficients, have been widely used to examine interactions among variables (Hao et al. 2017; He and Shi 2022; Ma et al. 2023). However, the effects of multiple factors on ESs involve complex interactions that are difficult to capture with linear models, limiting our understanding of their underlying mechanisms (Hao et al. 2017; Wang et al. 2024; Liu et al. 2025). The constraint-line method is effective in identifying the distribution limits or potential maxima of response variables under dominant constraints, thereby revealing key processes in complex systems (Liu and Wu 2021; Xu and Bao 2025). For example, Zhao and Dai (2024) applied this method to examine the relationship between the normalized difference vegetation index (NDVI) and ESs. Therefore, the constraint-line method provides a promising approach to elucidate how changes in fractional vegetation cover (FVC) influence ESs (Liu et al. 2023; Zhao and Dai 2024).

The Loess Plateau is one of the most ecologically vulnerable regions in the world, facing long-term pressures from ecological degradation and water scarcity (Fu et al. 2017; Ge et al. 2025). To improve regional environmental quality, China has implemented the Grain for Green Program (GFGP) since 1999, resulting in the conversion of 16,000 km<sup>2</sup> of cropland to vegetation on the Loess Plateau (Wang et al. 2022). However, these efforts have been controversial due to insufficient consideration of local precipitation conditions (Lv et al. 2019; Holl and Brancalion 2020). Despite growing attention to these issues, existing studies have largely treated the Loess Plateau as a whole using single-scale analyses. Systematic investigations of the threshold effects of FVC under different precipitation and topographic conditions remain lacking, which limits the ability to meet the demands of refined and differentiated ecological management (Zhou et al. 2023; Liu et al. 2025).

To address the aforementioned shortcomings, this study aims to: (1) systematically analyze the spatiotemporal evolution of FVC and three ESs (carbon sequestration, soil retention, and water yield) in the Loess Plateau from 2000 to 2022, using various quantitative assessment models; (2) evaluate the spatial correlation between FVC and ESs using Pearson correlation coefficients and independent t-tests; and (3) reveal the nonlinear relationships and threshold effects between FVC and ESs under different precipitation and topographic types using the constraint-line method. By examining the responses of ESs to FVC from multiple dimensions, this study assesses the potential risks of identifying FVC thresholds at a single scale and contributes to a

deeper understanding of their complex associations. It also provides scientific support for the refined management of ecological systems on the Loess Plateau.

## 2 Materials and Methods

### 2.1 Study Area

The Loess Plateau is located in the middle reaches of the Yellow River basin (33°43′–41°16′N, 100°54′–114°33′E), covering a total area of approximately 640,000 km<sup>2</sup>. It is the region with the highest concentration of loess globally and is also one of the areas most severely affected by soil erosion (Fig. 1a). Grassland is the largest land use type in this area, accounting for 58.81%, followed by cropland (23.46%) and forest land (10.37%) (Fig. 1b). The climate is primarily semi-humid and semi-arid, with an average annual temperature ranging from −13 to 17 °C, annual precipitation of 133 to 800 mm, and annual evaporation of 1400 to 2000 mm (Fig. 1c, d) (Ge et al. 2025). The topography is complex and diverse, with landforms such as plains, tablelands, hills, and mountains interspersed (Fig. 1e). Limited by a fragile ecological background and intense human activity interference, the regional ecosystem continues to bear immense pressure (Fu et al. 2017; Ge et al. 2025). With the implementation of large-scale ecological restoration projects, the Loess Plateau has become one of the regions in China with the most significant vegetation recovery. Therefore, this area is an ideal location to explore the mechanisms by which vegetation restoration impacts ESs.

### 2.2 Data Sources

The data utilized in this study includes vegetation data (including NDVI and net primary productivity (NPP)), digital elevation models (DEM), meteorological data (precipitation and evapotranspiration), and land use and soil data (available soil moisture content, maximum root depth, and proportions of sand, silt, clay, and organic carbon content). The formats, spatial resolutions, and sources of each dataset are summarized in Table 1. All data were resampled to a spatial resolution of 500 m and transformed to the WGS\_1984\_Albers projection coordinate system.

### 2.3 Methods

#### 2.3.1 Calculation of FVC

Using the pixel-based two-endmember model to calculate FVC (Eq. 1).

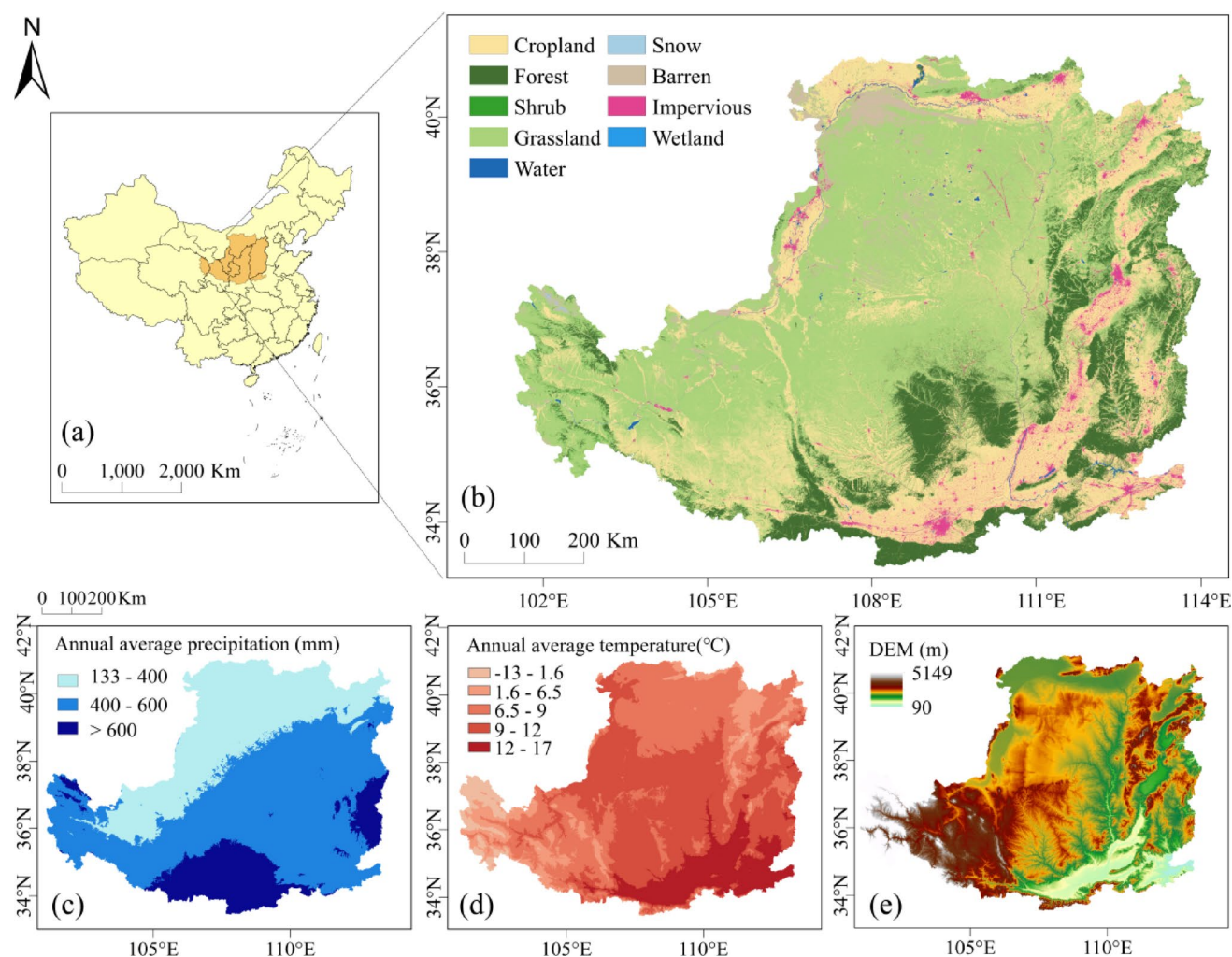


**Fig. 1** Study area overview. (a) Location in China; (b) Land use; (c) Annual average precipitation; (d) Annual average temperature; (e) DEM

**Table 1** Data sources

| Data Type          | Format | Time      | Spatial Resolution | Source                                                                                                                                                                                                                                                                       |
|--------------------|--------|-----------|--------------------|------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------------|
| DEM                | tiff   | –         | 30 m               | Earth System Science Data Cloud ( <a href="http://www.gscloud.cn">http://www.gscloud.cn</a> )                                                                                                                                                                                |
| Land Use           | tiff   | 2000–2022 | 30 m               | (Yang and Huang 2025)                                                                                                                                                                                                                                                        |
| Precipitation      | tiff   | 2000–2022 | 1 km               | National Earth System Science Data Center ( <a href="http://www.geodata.cn">http://www.geodata.cn</a> )                                                                                                                                                                      |
| Evapotranspiration | nc     | 2000–2022 | 1 km               |                                                                                                                                                                                                                                                                              |
| NDVI               | tiff   | 2000–2022 | 1 km               | NASA Land Processes Distributed Active Archive Center ( <a href="https://doi.org/10.5067/MODIS/MOD13A3.006">https://doi.org/10.5067/MODIS/MOD13A3.006</a> )                                                                                                                  |
| NPP                | tiff   | 2000–2022 | 500 m              | NASA Land Processes Distributed Active Archive Center ( <a href="https://lpdaac.usgs.gov/products/mod17a3hgv061/">https://lpdaac.usgs.gov/products/mod17a3hgv061/</a> )                                                                                                      |
| Soil Data          | tiff   | 2008      | 1 km               | Harmonized World Soil Database v 1.2 ( <a href="http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/">http://www.fao.org/soils-portal/soil-survey/soil-maps-and-databases/harmonized-world-soil-database-v12/en/</a> ) |

$$FVC = \frac{NDVI - NDVI_{soil}}{NDVI_{veg} - NDVI_{soil}} \quad (1)$$

where  $NDVI$ ,  $NDVI_{soil}$  and  $NDVI_{veg}$  represent the actual NDVI value of the area, the NDVI value of the non-vegetated area, and the NDVI value of the fully vegetated area, respectively.  $NDVI_{soil}$  and  $NDVI_{veg}$  are selected with

cumulative frequency thresholds of 5% and 95% for the NDVI values.

### 2.3.2 Assessment of ESs

(1) Carbon sequestration service.

This study employs NPP to characterize carbon sequestration services, a method widely utilized in research concerning the Loess Plateau (Wang et al. 2023; Zhao et al. 2020).

### (2) Soil retention service.

This study employs the revised universal soil loss equation (RUSLE) to calculate soil retention (Renard et al. 1997) (Eqs. 2–9).

$$Q_{sr} = R \times K \times L \times S \times (1 - C \times P) \quad (2)$$

$$R = 0.183P_m^{1.996} \quad (3)$$

$$K = \{-0.01383 + 0.51575 \times \{0.2 + 0.3 \times \exp[-0.0256 \times S_d(1 - S_i)/100]\} \times 0.3[S_i/(C_i + S_i)] \times \{(1 - 0.25C)/[C + \exp(3.72 - 2.95C)]\} \times [1 - 0.7 \times ((1 - S_d)/100)] / \{((1 - S_d)/100) + \exp[-5.51 + 22.9 \times ((1 - S_d)/100)]\} \times 0.1317 \quad (4)$$

$$L = \left( \frac{\alpha}{22.13} \right)^m \quad (5)$$

$$m = \frac{\beta}{1 + \beta} \quad (6)$$

$$\beta = \frac{\sin\theta/0.089}{3 \times \sin\theta^{0.8} + 0.56} \quad (7)$$

$$S = \begin{cases} 10.8\sin\theta + 0.03 & \theta < 5.14^\circ \\ 16.8\sin\theta - 0.55 & 5.14^\circ \leq \theta < 10.2^\circ \\ 21.91\sin\theta - 0.96 & 10.2^\circ \leq \theta < 28.81^\circ \\ 9.5988 & \theta \geq 28.81^\circ \end{cases} \quad (8)$$

$$C = \begin{cases} 1 & f = 0 \\ 0.6508 - 0.3436\log f & 0 < f \leq 78.3\% \\ 0 & f > 78.3\% \end{cases} \quad (9)$$

where  $Q_{sr}$  represents soil retention ( $t/hm^2$ );  $R$  denotes the rainfall erosion factor ( $MJ \cdot mm/(hm^2 \cdot h)$ );  $P_m$  is the precipitation in the  $m$ -th month (mm);  $K$  signifies the soil erodibility factor;  $S_d$ ,  $S_i$ , and  $C_i$  represent the contents of sand, silt, and clay, respectively (%);  $L$  and  $S$  denote the slope length and slope steepness factors, with  $m$  as the slope length exponent (dimensionless); and  $L$  and  $S$  are expressed in meters (m) and degrees ( $^\circ$ ), respectively;  $C$  is the vegetation cover factor (dimensionless), while  $f$  indicates the vegetation coverage (%); and  $P$  represents the management factor (dimensionless).

### (3) Water yield service.

This study employs the water yield module of the InVEST model to calculate the annual water yield in the Loess Plateau (Liu et al. 2025) (Eqs. 10–15).

$$Y_x = P_x - AET_x \quad (10)$$

$$AET_x/P_x = (1 + w_x R_x) / [1 + w_x R_{xj} + (1/R_x)] \quad (11)$$

$$R_x = (k_x \times ET_{0x}) / P_x \quad (12)$$

$$w_x = Z \times (AWC_x / P_x) \quad (13)$$

$$AWC_x = \text{Min}(MSD_x, RD_x) \times PAWC_x \quad (14)$$

$$PAWC = 54.509 - 0.132 \times SAN - 0.003 \times SAN^2 - 0.55 \times SIL - 0.006SIL^2 - 0.738 \times CLA + 0.007 \times CLA^2 - 2.688 \times C + 0.501 \times C^2 \quad (15)$$

where  $Y_x$ ,  $AET_x$ ,  $P_x$ , and  $ET_{0x}$  represent the annual water yield, actual evapotranspiration, precipitation, and potential evapotranspiration for grid cell  $x$  (mm);  $R_x$  denotes the aridity index (dimensionless);  $w_x$  is an empirical parameter (dimensionless) used to describe climate-soil properties;  $Z$  represents the Zhang coefficient, which characterizes the parameter of seasonal rainfall distribution and intensity;  $AWC_x$  and  $PAWC$  indicate the plant-available water content (mm) and plant-available water capacity (%) respectively;  $RD_x$  refers to the root depth of the vegetation (mm);  $MSD_x$  denotes the maximum soil depth (mm); and  $SAN$ ,  $SIL$ ,  $CLA$ , and  $C$  represent the contents of soil sand, silt, clay, and organic carbon, respectively (%).

### 2.3.3 Dynamic Trend Analysis

This study employs the Mann-Kendall test to analyze the long-term trends in FVC and various ESs (Haiping et al. 2019) (Eqs. 16–19).

$$\beta = \text{median} \frac{x_j - x_i}{j - i} \quad (1 < i < j < n) \quad (16)$$

$$Z = \begin{cases} \frac{S-1}{\sqrt{\text{Var}(S)}} & (S > 0) \\ 0 & (S = 0) \\ \frac{S+1}{\sqrt{\text{Var}(S)}} & (S < 0) \end{cases} \quad (17)$$

$$S = \sum_{i=1}^{n-1} \sum_{j=i+1}^n \text{sng}(x_j - x_i) \quad (18)$$

$$\text{sng}(x_j - x_i) = \begin{cases} 1 & (x_j - x_i > 0) \\ 0 & (x_j - x_i = 0) \\ -1 & (x_j - x_i < 0) \end{cases} \quad (19)$$

where  $\beta$  represents the trend of variation;  $x_j$  and  $x_i$  are the values of the time series data;  $j$  and  $i$  denote time; and  $n$  refers to the total number of observations. The variable  $\text{sig}$  is the significance factor, where the test statistic  $|Z| > 1.65$ , 1.96, and 2.58 indicates significance at the confidence levels of 90%, 95%, and 99%, respectively.

### 2.3.4 Spatial Correlation Analysis

This study utilizes the Pearson correlation coefficient to characterize the relationships between FVC and various ESs (Pearson et al. 2013) (Eq. 20).

$$R = \frac{\sum_{i=1}^n (x_i - \bar{x})(y_i - \bar{y})}{\sqrt{\sum_{i=1}^n (x_i - \bar{x})^2 \sum_{i=1}^n (y_i - \bar{y})^2}} \quad (20)$$

where  $R$  represents the correlation coefficient;  $x_i$  and  $y_i$  denote the FVC of the  $i$ -th year and the average FVC, respectively; and  $y$  represents the average values of carbon sequestration, soil retention, or water yield for that year. The correlation coefficient  $R$  ranges from  $[-1, 1]$ , with positive values indicating a positive correlation and negative values indicating a negative correlation. The significance of the correlation is assessed using the obtained  $p$  value; a  $p$  value of  $\leq 0.05$  indicates a significant correlation, while  $p > 0.05$  denotes a non-significant correlation.

This study employs an independent samples T-test to assess whether there are significant differences in ES levels between areas of significant vegetation recovery and those with non-significant recovery. This method is applicable to cases with unequal sample sizes and heterogeneous variances. The statistical hypotheses are as follows:  $H_0: \mu_1 = \mu_2$ ;  $H_1: \mu_1 > \mu_2$  (Eq. 21).

$$t = \frac{|\bar{x}_1 - \bar{x}_2|}{\sqrt{\frac{(n_1-1)s_1^2 + (n_2-1)s_2^2}{n_1+n_2-2} \times \frac{n_1+n_2}{n_1 \times n_2}}} \quad (21)$$

where  $\bar{x}_1$  and  $\bar{x}_2$ ,  $s_1^2$  and  $s_2^2$ ,  $n_1$  and  $n_2$  represent the means, variances, and sample sizes of the two groups, respectively. If  $t > t_{\alpha}$ , the null hypothesis at a significance level of 0.05 is rejected, indicating that there is a significant difference between the two groups. This suggests that the ESs in areas of significant vegetation recovery ( $\mu_1$ ) are notably greater than those in areas of non-significant recovery ( $\mu_2$ ).

### 2.3.5 Constrained line Method

ESs are influenced by a myriad of factors. FVC, as a primary limiting variable, exerts a significant constraint on its distribution, resulting in a nonlinear, scatter cloud-like two-dimensional distribution pattern (Thomson et al. 1996; Pitman et al., 2003). To minimize the impact of confounding factors on the analysis, this study employs the constrained line method to describe the relationships between FVC and ESs (Guo et al. 1998; Hao et al. 2017). The procedure involves four steps: First, a two-dimensional scatter plot is constructed to depict the relationship between FVC (limiting variable  $X$ ) and ESs (response variable  $Y$ ). Second, the theoretical range of FVC is divided into 100 equal intervals, from which the 95th percentile of ESs within each interval is extracted as constraint points. Third, a Restricted Cubic Spline (RCS) is applied to fit the constraint points, thereby obtaining the constrained line. Fourth, threshold values are quantitatively identified by analyzing the adjacent growth rate of the constrained line. Specifically, the inflection point—where ESs shift from increasing to decreasing or vice versa—is determined as the point at which the adjacent growth rate equals zero. When multiple inflection points are detected, the corresponding ESs values are compared, and the FVC associated with the maximum ESs value is selected as the threshold (Liu et al. 2025).

## 3 Results

### 3.1 Spatiotemporal Variation of FVC

From 2000 to 2022, FVC on the Loess Plateau increased from 20.35% to 36.55% (Fig. 2a). In 2000, low-FVC zones ( $\text{FVC} \leq 20\%$ ) accounted for over half of the area, decreasing to approximately one-third by 2022. Meanwhile, the proportions of medium-FVC zones ( $40\% \leq \text{FVC} \leq 60\%$ ) and high-FVC zones ( $60\% \leq \text{FVC} \leq 80\%$ ) increased from 13.19% to 25.2% and from 4.28% to 15.58%, respectively, indicating an overall increase in vegetation coverage.

Spatially, FVC in 2022 showed a pattern of higher values in the southeast and lower values in the northwest, with high-FVC areas mainly concentrated in the Lvliang Mountains, Taihang Mountains, and Qinling region (Fig. 2c, d). A total of 87.92% of the study area exhibited significant increases in FVC, whereas areas with no significant change accounted for only 1.81%, primarily located in the northwest (Fig. 2e). Areas with vegetation degradation were limited and mainly distributed around urban peripheries such as Xi'an, Taiyuan, and Yinchuan (Fig. 2e).

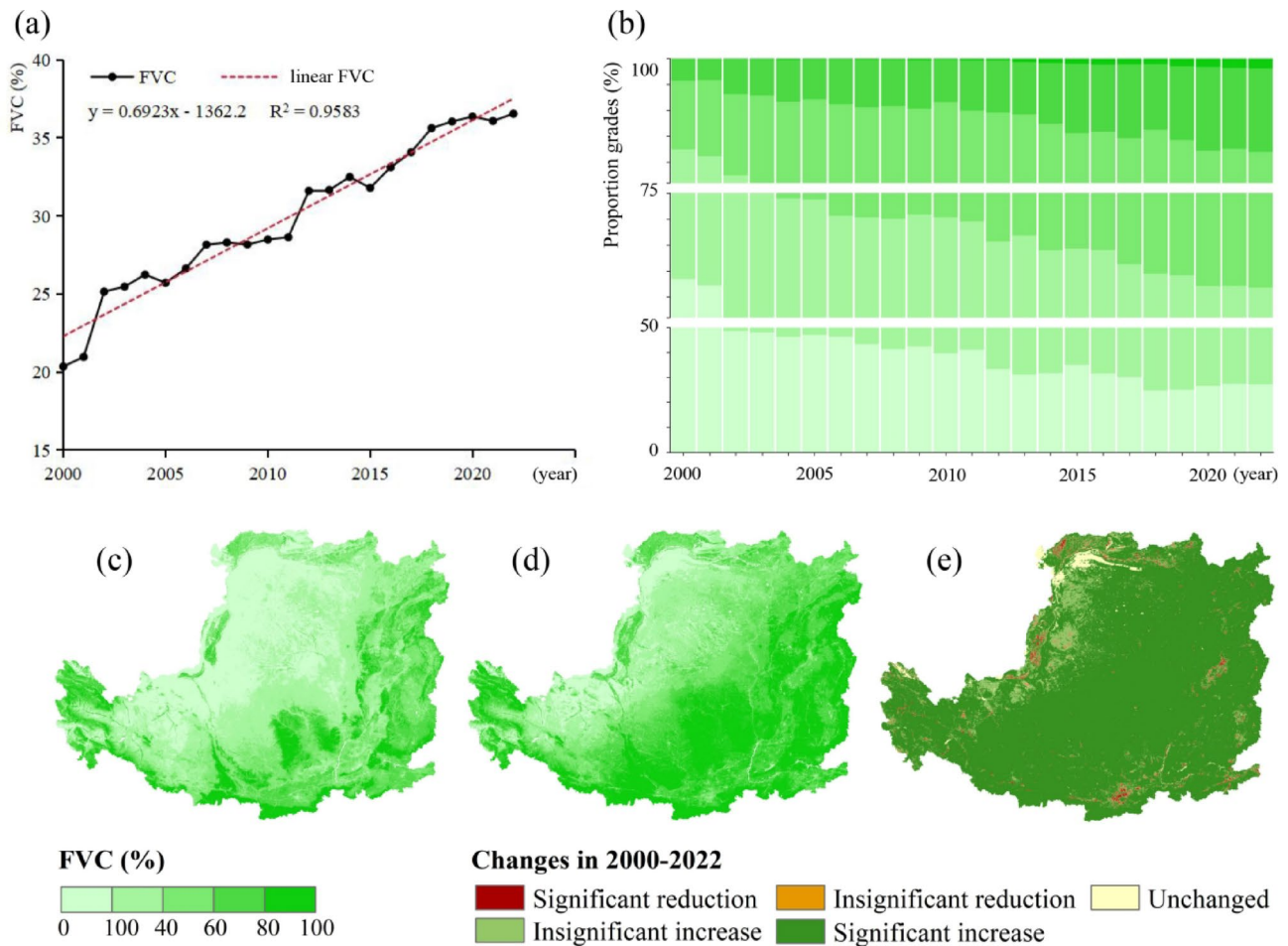


**Fig. 2** FVC Dynamics on the Loess Plateau from 2000 to 2022. **(a)** Changes in the annual average FVC; **(b)** Area proportions of different FVC classes; **(c)** Spatial distribution of FVC in 2000; **(d)** Spatial distribution of FVC in 2022; **(e)** Significance of FVC changes

### 3.2 Spatiotemporal Changes of ESs

From 2000 to 2022, all three primary ESs in the Loess Plateau showed marked increases (Fig. 3a–c). Carbon sequestration increased from 210.07 to 360.93 g C/m<sup>2</sup>. The proportion of areas exceeding 400 g C/m<sup>2</sup> rose from 4.78% to 44.21%, while areas below 200 g C/m<sup>2</sup> decreased substantially (Fig. 3a). Spatially, carbon sequestration exhibited a pattern of higher values in the southeast and lower values in the northwest. In 2000, values were mainly concentrated in the range of 100–200 g C/m<sup>2</sup> (33.08%), whereas by 2022, areas exceeding 400 g C/m<sup>2</sup> became dominant (44.21%). Overall, 88.43% of the region showed increases, while areas with declines accounted for less than 1%.

Soil retention also increased, with the annual average rising from 162.2 to 201.7 t/hm<sup>2</sup> (Fig. 3b). Areas exceeding 500 t/hm<sup>2</sup> expanded from 13.24% to 32.00%, and the spatial distribution was similar to that of carbon sequestration. The proportion of areas with values between 0 and 100 t/hm<sup>2</sup> decreased from 55.95% to 50.93%. In total, 82.15% of

the area exhibited increases, whereas only 0.68% showed decreases.

Water yield increased from 353.49 to 437.61 mm (Fig. 3c). In 2000, values of 300–450 mm dominated (34.75%), while in 2022, the dominant range shifted to 450–600 mm (41.36%). The spatial pattern remained higher in the southeast and lower in the northwest. In contrast to the other ESs, increases were observed in only 22.66% of the area, mainly in the southwest and eastern regions.

### 3.3 Spatial Correlation between FVC and ESs

FVC shows a positive correlation with both carbon sequestration and soil retention, with significantly positive areas accounting for 83.72% and 84.64% of the total area, respectively (Fig. 4a, b, d). In contrast, the spatial correlation between FVC and water yield is more heterogeneous. Significantly positive areas account for 36.51% of the total and are mainly concentrated in the central and western regions, whereas significantly negative areas account for 11.85%

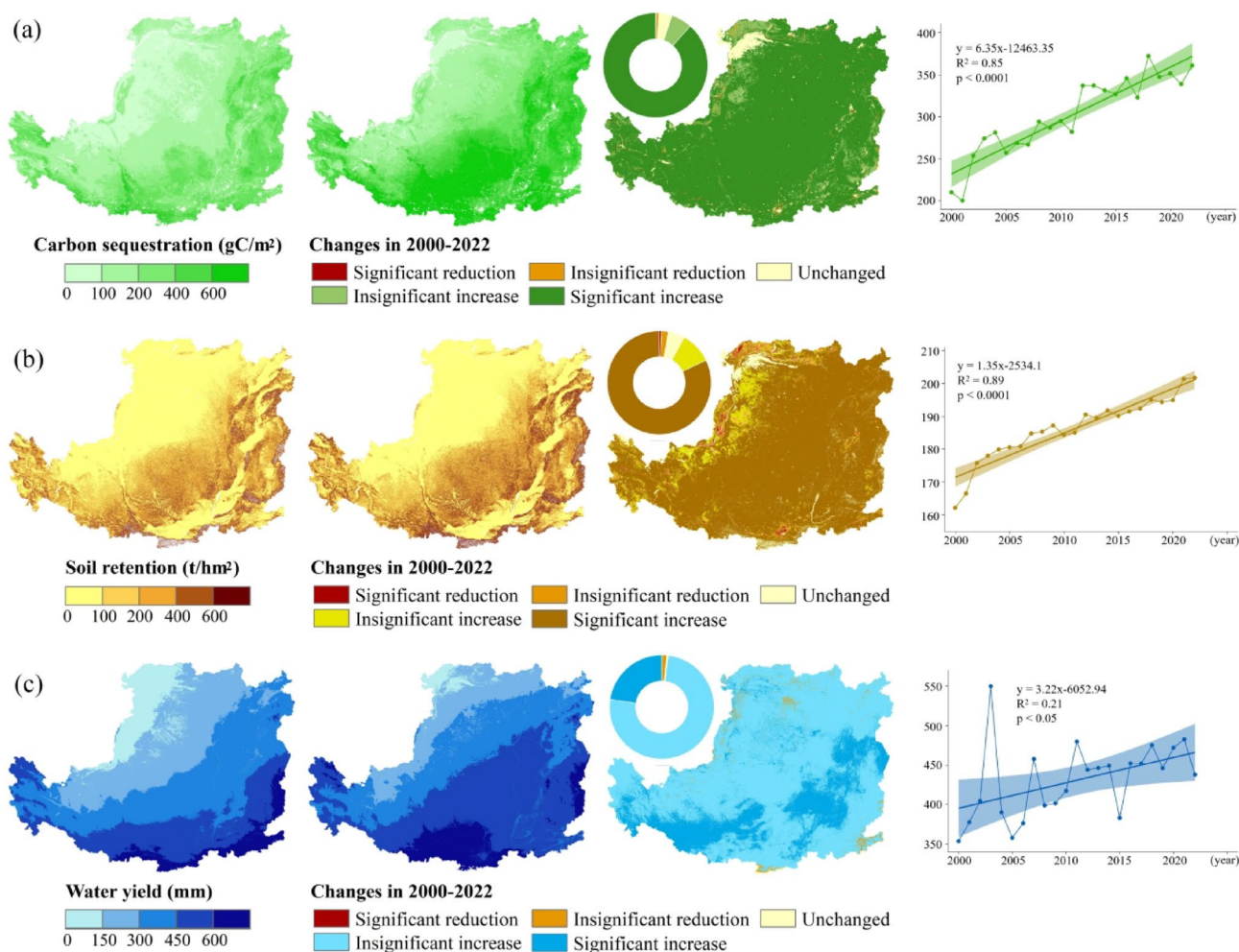


**Fig. 3** Spatial pattern and significant distribution of three ESs on the Loess Plateau from 2000 to 2022. (a) Carbon sequestration; (b) Soil retention; (c) Water yield

and are primarily distributed in the southwest and northwest (Fig. 4c, d).

An independent t-test was conducted to further assess the impact of FVC increase on ESs. The results show that the t-values for carbon sequestration, soil retention, and water yield are 4.387, 5.080, and 2.461, respectively, all exceeding the critical value of 1.96 (Fig. 4e). The corresponding p-values are 0.000 ( $< 0.01$ , highly significant), 0.000 ( $< 0.01$ , highly significant), and 0.014 ( $< 0.05$ , significant), respectively, all passing the significance tests. These findings demonstrate that the level of ESs in areas with significant increases in FVC is markedly higher than in areas without significant increases.

### 3.4 Nonlinear Relationships and Thresholds between FVC and ESs

#### 3.4.1 FVC and Carbon Sequestration

Overall, the relationship between FVC and carbon sequestration on the Loess Plateau follows a unimodal pattern, characterized by an initial increase followed by a decline (Fig. 5a). As FVC increases, carbon sequestration increases, peaking at 770.18 g C/m<sup>2</sup> at an FVC of 77.19%. Beyond this threshold, carbon sequestration declines.

In different precipitation zones, the relationships between FVC and carbon sequestration also exhibit similar unimodal patterns (Fig. 5b–d). In arid and semi-arid regions (annual precipitation  $< 400$  mm), the peak carbon sequestration is 511.62 g C/m<sup>2</sup> at an FVC of 41.58% (Fig. 5b). In semi-humid areas (400–600 mm), the peak reaches 700.11 g C/m<sup>2</sup> at an FVC of 74.31% (Fig. 5c). In humid regions ( $> 600$  mm), the peak is 780.83 g C/m<sup>2</sup> at an FVC of 76.51% (Fig. 5d).

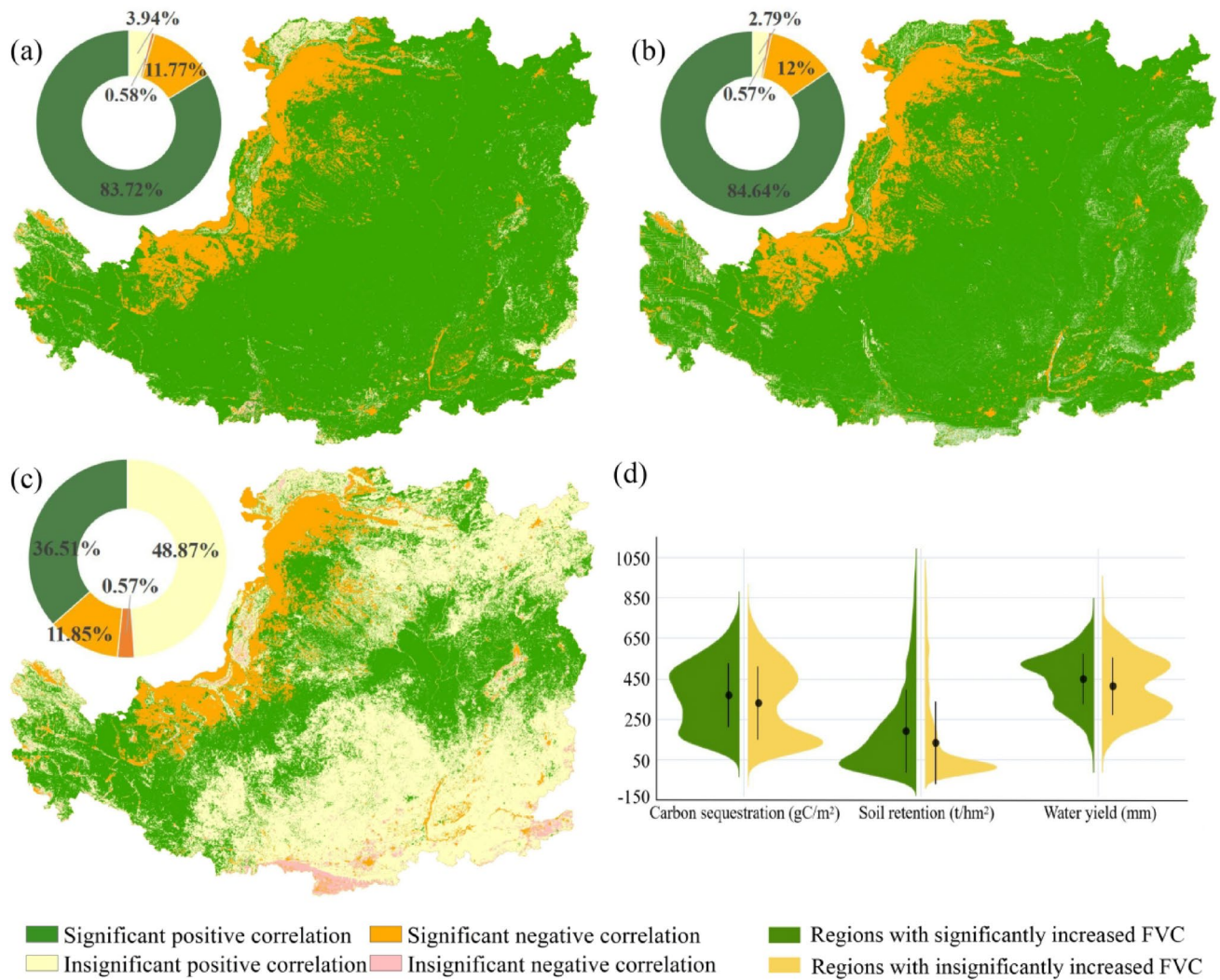


**Fig. 4** Spatial correlation between FVC and ESs on the Loess Plateau. (a) FVC and carbon sequestration; (b) FVC and soil retention; (c) FVC and water yield; (d) Independent samples t-test

Across different topographic zones, the relationships consistently follow a unimodal pattern (Fig. 5e–h). In plain areas, carbon sequestration reaches  $707.33 \text{ g C/m}^2$  at an FVC of 72.23% (Fig. 5e). In tableland regions, it reaches  $741.32 \text{ g C/m}^2$  at an FVC of 71.42% (Fig. 5f). In hilly areas, the peak value is  $778.90 \text{ g C/m}^2$  at an FVC of 75.01% (Fig. 5g), while the highest value occurs in mountainous regions at  $791.88 \text{ g C/m}^2$  at an FVC of 77.56% (Fig. 5h).

### 3.4.2 FVC and Soil Retention

Overall, the relationship between FVC and soil retention on the Loess Plateau shows a unimodal pattern, with soil retention first increasing and then decreasing as FVC rises (Fig. 6a). The maximum soil retention ( $1391.86 \text{ t/hm}^2$ ) occurs at an FVC of 72.91%, after which further increases in FVC lead to a decline.

Across different precipitation zones, the FVC–soil retention relationships vary in shape. In arid and semi-arid regions (annual precipitation  $< 400 \text{ mm}$ ), a bimodal pattern is observed, with a peak of  $488.31 \text{ t/hm}^2$  at an FVC of 41.34% (Fig. 6b). In semi-humid regions ( $400\text{--}600 \text{ mm}$ ), the relationship is unimodal, reaching  $1406.48 \text{ t/hm}^2$  at an FVC of 69.1% (Fig. 6c). In humid regions ( $> 600 \text{ mm}$ ), the curve is relatively smooth, with a maximum of  $1566.66 \text{ t/hm}^2$  at an FVC of 75.78% (Fig. 6d).

Across topographic zones, the relationship consistently follows a unimodal pattern. The curves for plain and tableland areas show greater variability, whereas those for hilly and mountainous areas are smoother. Peak soil retention reaches  $750.77 \text{ t/hm}^2$  at an FVC of 65.4% in plains (Fig. 6e) and  $1079.19 \text{ t/hm}^2$  at 63.67% in tablelands (Fig. 6f). Higher values are observed in hilly ( $1501.6 \text{ t/hm}^2$  at 73.15%;

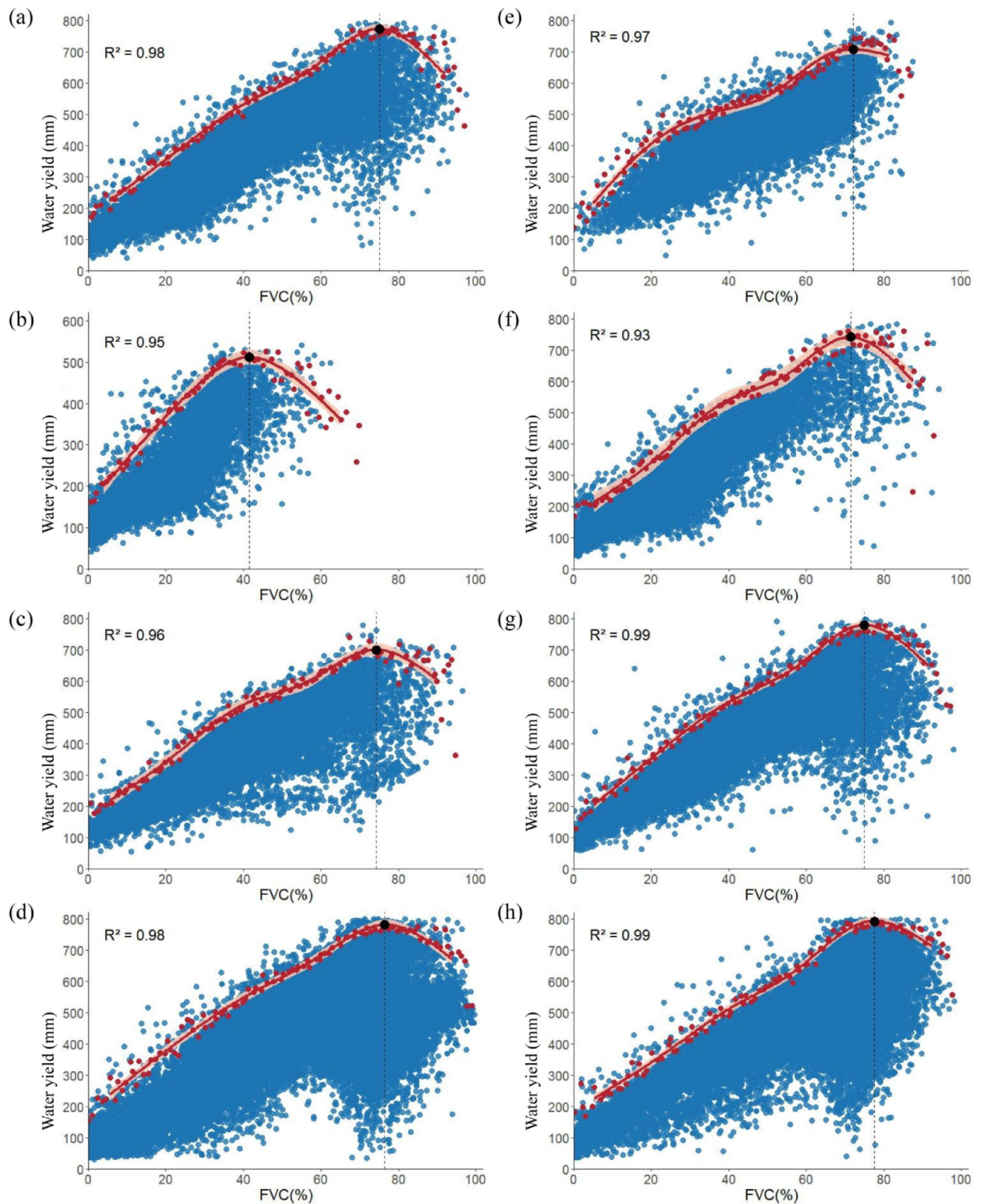


**Fig. 5** Nonlinear relationships between FVC and carbon sequestration and their thresholds. (a) Overall; (b) Arid and semi-arid regions; (c) Semi-humid areas; (d) Humid regions; (e) Plains; (f) Tablelands; (g) Hilly areas; (h) Mountainous regions

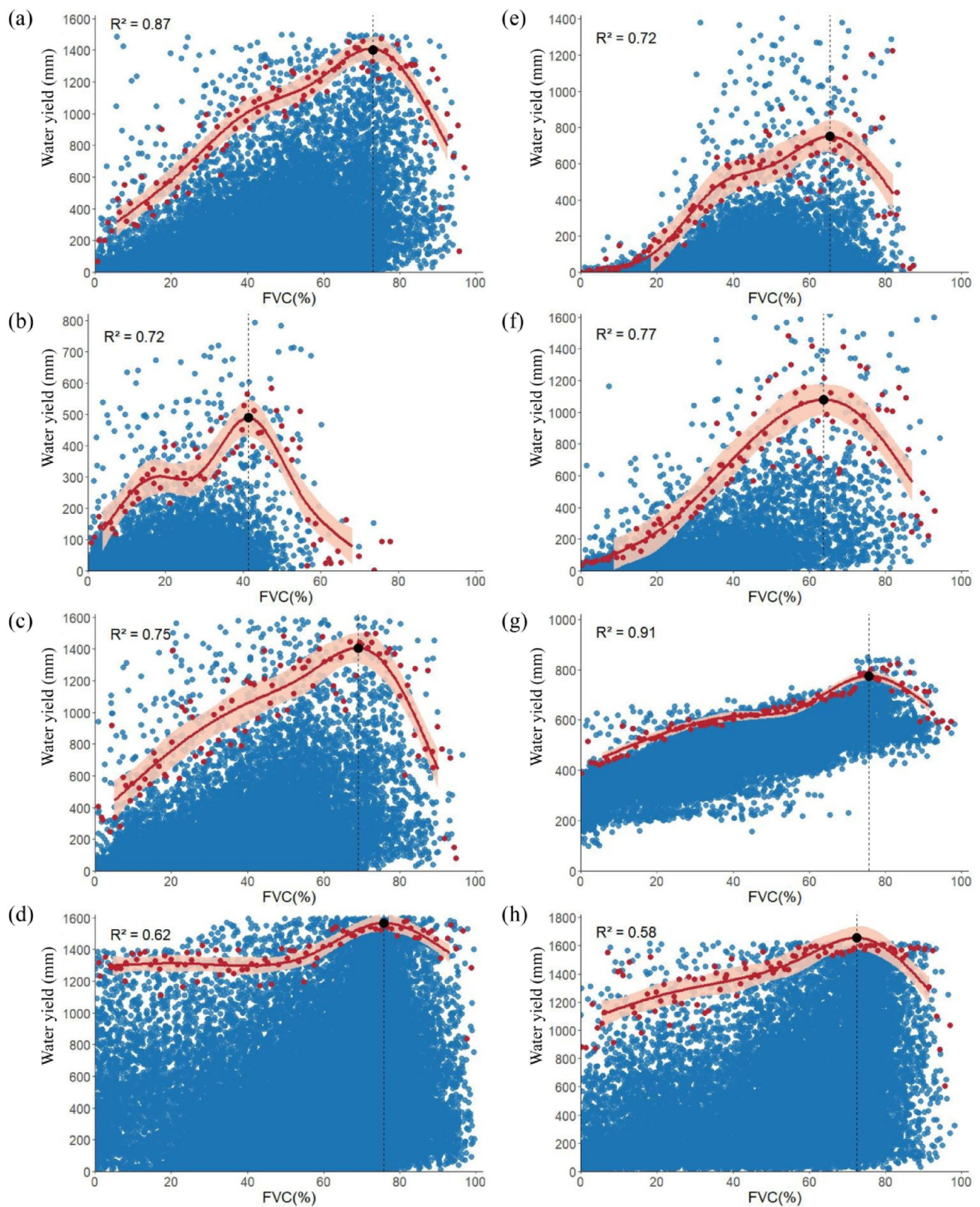


**Fig. 6** Nonlinear relationships between FVC and soil retention and their thresholds. (a) Overall; (b) Arid and semi-arid regions; (c) Semi-humid areas; (d) Humid regions; (e) Plains; (f) Tablelands; (g) Hilly areas; (h) Mountainous regions

Fig. 6g) and mountainous areas (1654.71 t/hm<sup>2</sup> at 72.53%; Fig. 6h).

### 3.4.3 FVC and Water Yield

Overall, the relationship between FVC and water yield on the Loess Plateau shows a nonlinear fluctuating pattern, characterized by an initial increase followed by a decline (Fig. 7a). Unlike carbon sequestration, water yield shows no clear increasing trend with rising FVC and varies within a relatively narrow range. The peak occurs at an FVC of 72.01%, reaching 819.22 mm, after which it declines.

Across different precipitation zones, the relationship between FVC and water yield varies considerably (Fig. 7b–d). In arid and semi-arid regions (annual precipitation < 400 mm) and semi-humid areas (400–600 mm), water yield is relatively insensitive to changes in FVC, and no pronounced peak is observed (Fig. 7b, c). In humid regions (> 600 mm), the relationship exhibits a hump-shaped pattern, with water yield increasing as FVC rises from 55% to 77.92%. The peak occurs at an FVC of 77.92%, reaching 825.04 mm, followed by a decline (Fig. 7d).

Across different topographic zones, the relationships also vary (Fig. 7e–h). In plain areas, the relationship remains relatively stable, with a peak of 381.52 mm at an FVC of 67.13% (Fig. 7e). In both tableland and hilly regions, unimodal patterns are observed. The tableland region reaches a peak of 721.97 mm at an FVC of 70.21% (Fig. 7f), while the hilly region peaks at 774.17 mm at an FVC of 75.57% (Fig. 7g). In mountainous regions, a hump-shaped pattern is observed. Below 60% FVC, changes in FVC have little effect on water yield, whereas between 60% and 79.51%, water yield increases and reaches a peak of 848.76 mm (Fig. 7h).

## 4 Discussion

### 4.1 Potential Risks of Identifying FVC Thresholds at a Single Scale

The results indicate that the overall FVC threshold on the Loess Plateau is comparable to those observed in humid and mountainous regions, yet significantly higher than those in arid and semi-arid or plain areas (Figs. 5, 6 and 7). For example, the FVC threshold for carbon sequestration across the entire Loess Plateau reaches 77.19%, closely aligning with the threshold in humid regions (76.51%), but markedly exceeding that in arid and semi-arid regions (41.58%) (Fig. 5a and d). Similar patterns are observed for water yield and soil retention services (Figs. 6a and d and 7a and d).

This discrepancy reveals a pronounced scale effect: aggregated thresholds obscure environmental heterogeneity and tend to overestimate vegetation restoration potential in water-limited regions (Cao et al. 2016; Bai et al. 2020; Fu et al. 2024). From an ecological perspective, this reflects the principle of resource limitation, whereby water availability constitutes the primary constraint on vegetation growth and ecosystem functioning in arid and semi-arid environments (Liu et al. 2025). When spatial variability in precipitation and terrain is ignored, the derived “overall threshold” disproportionately reflects conditions in relatively favorable (e.g., humid or topographically complex) areas, leading to inflated estimates of achievable vegetation coverage.

Consequently, applying such generalized thresholds across the Loess Plateau may lead to a mismatch between vegetation water demand and regional water supply, thereby obscuring spatial differences in ecological restoration needs and recovery capacities. This mismatch not only reduces the accuracy of ecological assessments but also risks establishing unrealistic restoration targets. Importantly, in arid and semi-arid regions where vegetation growth is tightly constrained by soil moisture and groundwater recharge, excessive increases in FVC can intensify evapotranspiration, reduce soil water storage, and disrupt the local water balance, while also enhancing rainfall interception and reducing surface runoff generation (Liu et al. 2025). This may trigger a negative feedback loop in which increased vegetation cover leads to higher water consumption, subsequently causing soil moisture depletion, vegetation stress, and eventual ecosystem degradation (Feng et al. 2016; Zhang et al. 2018; Li et al. 2021).

China's vast arid and semi-arid regions, home to approximately 580 million people (Fu et al. 2024), are already facing severe water scarcity challenges (Feng et al. 2016; Hu et al. 2021). Under such conditions, vegetation restoration must be guided by regional water resource carrying capacity rather than the blind pursuit of high FVC. Empirical evidence supports this concern: in the Mu Us Sandyland, a key ecological restoration region in northern China, terrestrial water storage declined at an average rate of  $16.6 \pm 5.0$  mm yr<sup>-1</sup> following large-scale restoration efforts (Zhao et al. 2020).

Therefore, in regions approaching or exceeding ecological thresholds, restoration strategies should shift from maximizing vegetation coverage to optimizing vegetation structure and ecological function. This includes prioritizing drought-resistant native species, regulating planting density, adopting water-saving irrigation practices, and promoting shrub–grass combinations. Such an approach can enhance ecosystem resilience while maintaining a sustainable balance between vegetation growth and water resource availability, ultimately improving the diversity, stability, and

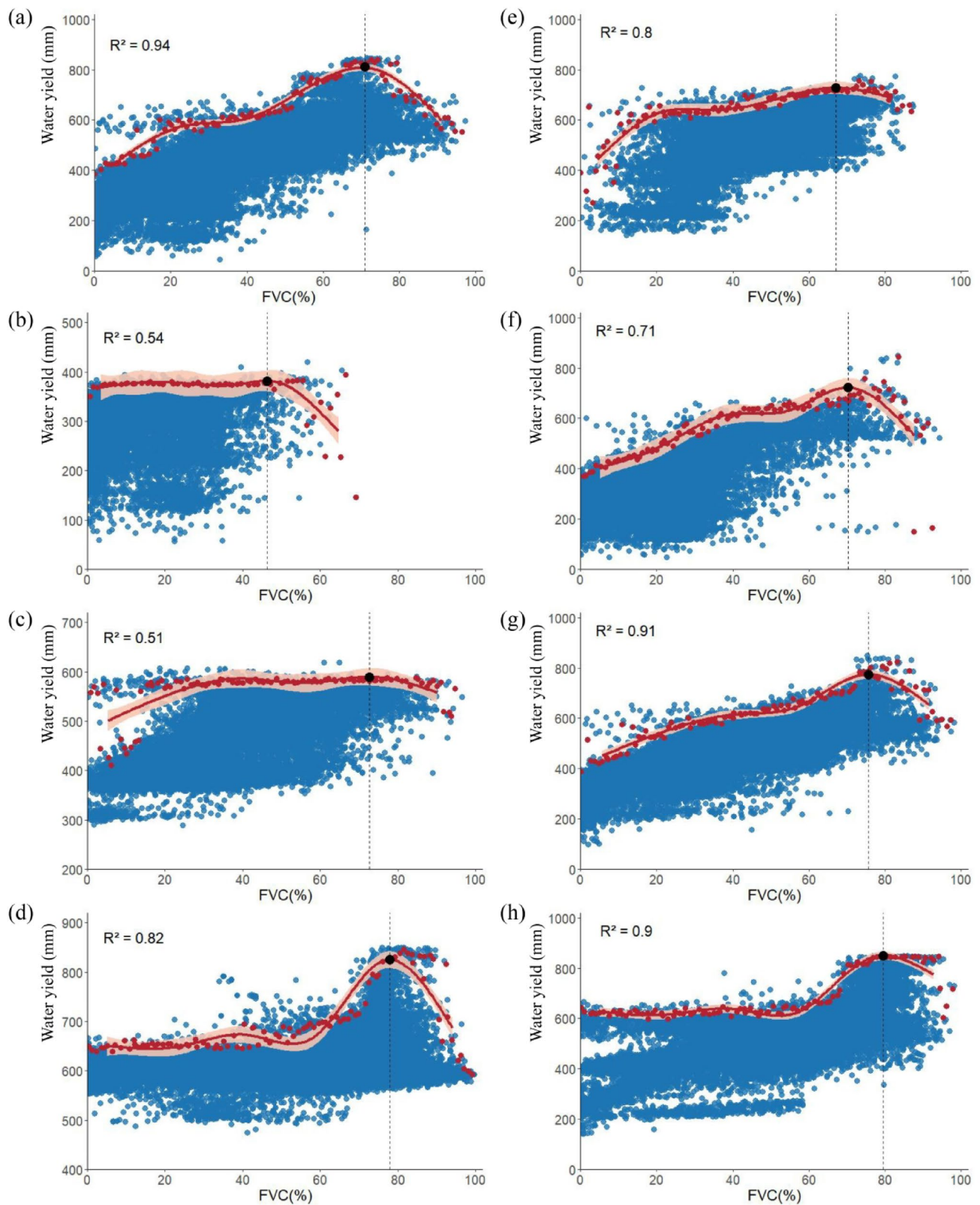


**Fig. 7** Nonlinear relationships between FVC and water yield and their thresholds. (a) Overall; (b) Arid and semi-arid regions; (c) Semi-humid areas; (d) Humid regions; (e) Plains; (f) Tablelands; (g) Hilly areas; (h) Mountainous regions

sustainability of ESs (Cortinovis et al. 2021; Hegwood et al. 2022; Chen et al. 2024; Zhou et al. 2024).

## 4.2 Threshold Effects of FVC on ESs from Multidimensional Perspectives

The spatial differentiation of ecosystems and their functions is fundamentally governed by natural geographical gradients, among which climate (especially precipitation) and topography play dominant roles (Wang et al. 2022; Moyo et al. 2023; Zhou et al. 2025). On the Loess Plateau, precipitation directly controls vegetation growth and water availability, while topography regulates hydrological processes, soil erosion, and nutrient redistribution (Duan et al. 2016; Feng et al. 2023). From an ecological mechanism perspective, precipitation primarily determines resource supply, whereas topography influences resource redistribution and process intensity (Moyo et al. 2023). Based on this framework, this study systematically examines the threshold effects of FVC on ESs across these two dimensions.

A comparison of FVC thresholds under different precipitation zones and landform types reveals four key characteristics.

First, FVC thresholds exhibit significantly greater sensitivity to precipitation gradients than to topographic variation. For example, the FVC threshold for carbon sequestration increases from 41.58% in arid and semi-arid regions to 76.51% in humid regions, representing a difference of 34.93% points (Fig. 5b and d). In contrast, the variation across topographic zones is only 5.33% points (72.23% in plains versus 77.56% in mountainous areas; Fig. 5e and h). Similar patterns are observed for water yield and soil retention services, where threshold differences across precipitation zones (34.44 and 31.71% points, respectively) far exceed those across topographic zones (9.75 and 12.38% points; Figs. 6b and h and 7b and h). These findings indicate that moisture availability acts as the dominant limiting factor, directly constraining vegetation productivity and setting the upper bounds of ecosystem service enhancement. In contrast, topography mainly modulates local processes such as runoff routing and erosion intensity, resulting in comparatively smaller impacts on threshold values.

Second, among the three ESs, FVC thresholds for water yield and soil retention are more sensitive to topographic variation than those for carbon sequestration. Specifically, the variation in thresholds across topographic zones reaches 12.38 and 9.75% points for water yield and soil retention, respectively, compared to only 5.33% points for carbon sequestration (Figs. 5e and h, 6e and h and 7e and h). This suggests that topography exerts stronger control over process-based ESs—particularly those related to surface runoff

generation and soil erosion—than over biomass-dependent services such as carbon sequestration.

Third, the comparison of FVC thresholds across precipitation zones reveals a clear nonlinear pattern: the increase in thresholds from arid and semi-arid to semi-humid regions is substantially greater than that from semi-humid to humid regions. For example, the carbon sequestration threshold increases by 32.73% points between arid/semi-arid and semi-humid regions, but by only 2.20% points between semi-humid and humid regions (Fig. 5b and d). Similar trends are observed for soil retention and water yield services (Figs. 6b and d and 7b and d). This pattern reflects a diminishing marginal effect of precipitation, whereby initial increases in water availability significantly alleviate water limitation and enhance ecosystem functioning, while further increases under already moist conditions yield relatively smaller gains.

Fourth, comparisons across topographic zones show high consistency within grouped landforms, with minimal differences between plains and tablelands, as well as between hilly and mountainous areas. For instance, the FVC threshold for carbon sequestration differs by only 0.81% points between plains and tablelands, while soil retention and water yield services show differences of 1.73 and 3.08% points, respectively. Similarly, differences between hilly and mountainous areas are negligible (Figs. 5e and h, 6e and h and 7e and h). This grouped consistency suggests that landforms with similar geomorphological characteristics share comparable hydrological and erosion dynamics, leading to functional convergence in ecosystem service responses to vegetation coverage.

Overall, these findings highlight that the threshold effects of FVC on ESs are jointly regulated by climatic constraints and topographic modulation, with precipitation playing a dominant role in determining threshold magnitude and topography shaping process sensitivity. Recognizing these multidimensional controls provides a practical foundation for ecological restoration by supporting the identification of region-specific FVC targets, optimizing the allocation of restoration efforts along precipitation gradients, and avoiding over-restoration in water-limited areas.

## 4.3 Limitations and Future Directions

This study has certain limitations and can be further improved in future research. First, this study focuses on three ESs—carbon sequestration, water yield, and soil retention—and does not fully capture the diversity of ESs on the Loess Plateau (Cortinovis et al. 2021; Hegwood et al. 2022; Xiong et al. 2025). Future studies should incorporate additional key services, such as sand fixation and biodiversity,

to more comprehensively represent the region's ecological functions (Bai et al. 2021; Cortinovis et al. 2021).

Second, although the InVEST model is widely used for large-scale ES assessment, its representation of ES generation mechanisms is relatively simplified, which limits its ability to fully capture the complexity of ecological processes and may introduce uncertainty in the results (Wang et al. 2025; Zhou et al. 2025). Future research could improve the robustness and accuracy of assessments through multi-model comparisons and the integration of process-based models.

Third, this study primarily examines the effects of precipitation and landform types on FVC thresholds, without considering other important environmental factors such as temperature, soil conditions, and land use (Felipe-Lucia et al. 2020; Nunes et al. 2022; Zhao et al. 2022). Future studies should incorporate additional key drivers and systematically explore the mechanisms by which FVC affects ESs across multiple environmental gradients and their interactions (Liu et al. 2024).

## 5 Conclusions

Understanding how vegetation restoration influences ESs is critical for sustainable management in water-limited regions. This study quantified the spatiotemporal dynamics of FVC and multiple ESs on the Loess Plateau from 2000 to 2022, and revealed their nonlinear relationships and threshold effects across climatic and topographic gradients.

Vegetation restoration has markedly improved ESs, with increases in carbon sequestration, soil retention, and water yield, all showing a southeast–northwest gradient. FVC is strongly positively correlated with carbon sequestration and soil retention, whereas its relationship with water yield is more complex and spatially heterogeneous, reflecting hydrological trade-offs.

The identified FVC thresholds exhibit clear environmental dependence. The regional “overall threshold” is largely shaped by humid and mountainous areas, leading to an overestimation of restoration potential in arid and semi-arid regions. Applying such generalized thresholds may therefore create mismatches between vegetation water demand and regional water availability, increasing ecological risks.

From a multidimensional perspective, FVC threshold effects are jointly controlled by climatic constraints and topographic modulation. Precipitation determines threshold magnitude, while topography regulates process sensitivity, particularly for water yield and soil retention. A nonlinear response to precipitation is observed, with diminishing marginal effects under increasing moisture. These findings provide a scientific basis for region-specific restoration

strategies and improved ecosystem management in dryland regions.

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**Data Availability** All data used in this study are described in Sect. 2.2.

## Declarations

**Conflict of interest** The authors declare that they have no conflict of interest.

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